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13. ABSTRACT (Maximum 200 words)

This report results from a contract tasking with Trinity College as follows: The contractor will investigate and develop an ad hoc wireless communications and data network that will efficiently integrate with existing internet and PSTN. The development will include a smart reliability network layer that will liaise with the application layer and the physical layer (in this case, a software radio) of the network. The smart reliability layer will combine elements of heuristics and fuzzy logic to determine the amount of Forward Error Correction (FEC) to use. The contractor will review existing wireless link and network protocols to establish and maintain state-of-the art, then develop and implement a PSTN gateway. The effort shall include the adaptation and extension of existing protocols which will be incorporated with the software radio to dynamically optimize routes across the ad-hoc network. The contractor shall document the development in a series of interim reports and as well as a conclusive final report as detailed in the technical proposal.

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Project Title: A Low Power, Medium Range, Ad-Hoc Multimedia Network

Final Report

August 31st 2000

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Abstract

This report outlines the work carried out on Air Force funded activities within our research group aimed at developing a prototype ad-hoc network using commercial off-the-shelf technology that will allow users of handheld computers equipped with wireless interfaces to use common networked multimedia applications. The report summarises the main stages of the project and concludes with some thoughts on promising future directions.

1. Introduction

Ad-hoc networks are networks where there is no fixed structure. Each node in the network may act like a switch, forwarding on data to another node. Since there is no central controlling point, such as a base station at the centre of a cell in a mobile phone network, there is no central point of failure. The distributed nature of such a network give the effect of a network that 'manages itself', allowing nodes to join and leave the network at any time and allowing all nodes on the network to communicate with each other. Some nodes on the ad-hoc network may act as gateway nodes to the Internet or to the PSTN, allowing all users on the network Internet and normal telephone services.

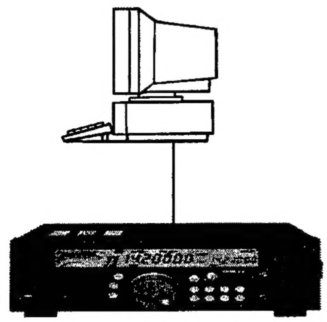
The aim of this project was to develop an ad-hoc network that was easily deployable and could be connected to a fixed network via a gateway node in the network. In particular the project proposal listed review, evaluation and adaptation of existing wireless link and network protocols as the main focus of work. The project did in fact go beyond these original plans and an extremely flexible ad-hoc network was designed.

2. Project Milestones

As stated in the introduction the main work in the project proposal was a review, evaluation and adaptation of existing wireless link and network protocols so that suitable software could be developed the ad-hoc network. *The results of this investigation were presented in the second interim report and will not be repeated here.* It was also necessary to develop a hardware platform on which the software would run. In designing and developing a suitable software and hardware architecture the project followed a number of distinctive phases.

2.1 Initial Solution

When the work on the project began it was planned to concentrate on the routing protocols and to use off-the-shelf radios for the nodes of the ad-hoc networks. It was decided to implement the network at amateur radio frequencies. Figure 1 shows an example node of these ad-hoc networks.



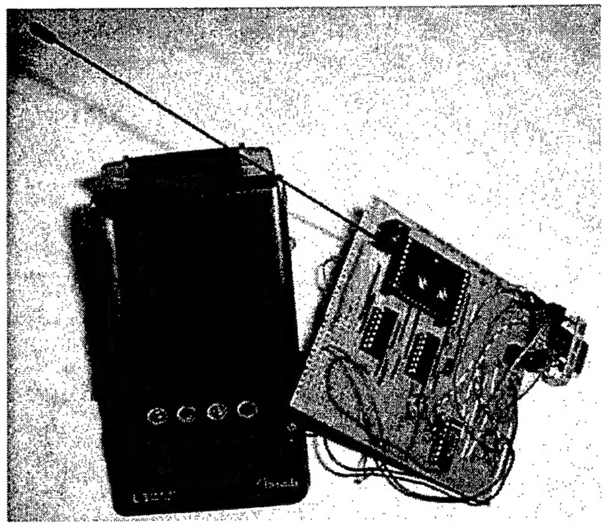
Ad-hoc Network Node Phase 1
Figure 1

2.2 Revised Solution

It became clear that the proposed hardware and software architecture was very cumbersome and a totally new software and hardware ad-hoc architecture was designed. The new platform still used off-the-shelf components but was cheaper and far more flexible.

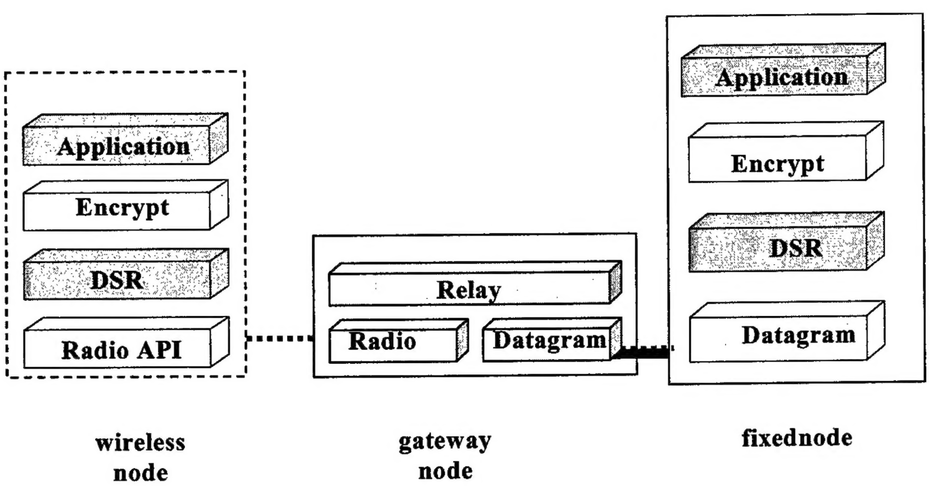
The phase 2 ad-hoc node consisted of a radio and a handheld device. The radio consisted of 40 kbit/s UHF radios developed by the project team. The principal advantage to using a custom built radio was that it allowed our project team to have complete control over packet formats, media access control etc rather than attempting to run ad-hoc networking protocol on top of protocols built into the radio hardware.

The handheld device was a HP PDA running Windows CE. The radio circuit together with the power supply had approximate dimensions 2cm x 8cm x 6cm and could be fixed easily to the back of the handheld device. The HP PDA communicated with the radio via the serial port. Figure 2 shows an early prototype of the ad-hoc network node.



Ad-hoc Network Node Phase 2
Figure 2

A highly modular layered framework was designed to cater for the software that was needed on each node of the ad-hoc network. Each node of the network had its own stack; the layers of the stack consist of the appropriate building blocks such as an ad-hoc routing block or an encryption block. A 'generic layer' interface that allows the dynamic assembly of a stack was created. The multi-threading and synchronisation facilities available in the handheld device environment were used to design this generic layer architecture. Each layer runs as an independent thread and interacts with its neighbouring layers in very simple, clearly defined ways. The set of layers is assembled at runtime to form a complete protocol stack. Figure 3 shows a schematic of three nodes of an ad-hoc network with the appropriate layers on each node of the network.



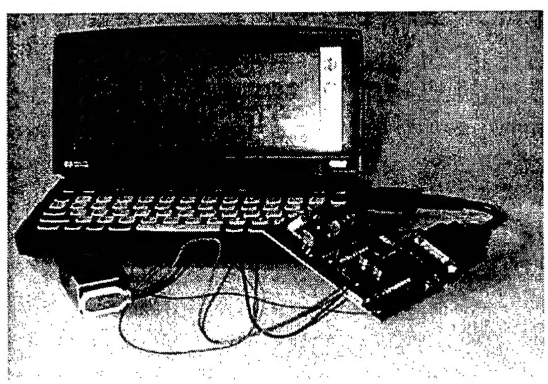
Ad-hoc network Layered Architecture
Figure 3

The wireless node has a layer for controlling the radio, onto which can be placed a variety of media access control and/or network routing protocols. Our main implementation within this project used an on-demand Ad-Hoc network routing protocol called Dynamic Source Routing (DSR) and in the future we are planning to augment this with a range of different protocols such as the Zone Routing Prototocol (ZRP) and a variation of the piconet protocol used in the Bluetooth system.

Irrespective of which networking protocol is in use, a variety of application and application-support layers can be placed on top of the lower part of the stack. Figure 3 shows an encryption layer (implementing the Blowfish algorithm) and an application layer (e.g. WWW access_. The gateway node allows access to a fixed network via the relay layer. The gateway node also has software for controlling the radio as well as what we term a datagram layer. This datagram layer is based on the use of sockets and allows communication across the fixed network. It also enables the simulation of physical media such as radio broadcasting and IrDA, by configuring a node sockets appropriately.

2.3 Advanced Solution

In the third phase of the project the ad-hoc node was further improved. The radio circuit was advanced. The software was ported to a Pocket PC. The Pocket PC is a more powerful device and supports multimedia applications. In this stage of the project a large number of extra layers (e.g. for error checking and encryption) were developed and the chosen ad-hoc routing protocol is use was streamlined. Figure 4 shows the latest ad-hoc network node.



Ad-hoc Network Node Phase 3
Figure 4

3. Conclusions

The ad-hoc network designed over the duration of this project proved to be successful. The nodes of the network are light and small. The software at each node is flexible and easily configurable. The system allows for easy testing of a variety of network routing protocols of interest. Internet access is available to all nodes in the network via the gateway node. This has been extensively tested. Streaming audio has also been tested on the network.

4. Future Work

Within the scope of this project, we have developed a test-bed system that allows a variety of ad-hoc protocols to be easily built and deployed in a real wireless network. We intend to use this test-bed to provide new insights into the properties of existing ad-hoc protocols and to assist us in the design of hybrid and totally new protocols addressing this area.

We have developed a number of very simple applications, and in the future, we would like to add to this list. In particular, we would like to develop a general purpose one-to-one and many-to-many voice conferencing system, which coupled with the appropriate group security mechanisms would function as an extremely flexible field communications system. Other application areas that we will pursue involve new approaches to group broadcasting and position-aware applications.

SPC 99-4086

Project Title: A Low Power, Medium Range, Ad-Hoc Multimedia Network

2nd Interim Report

April 20th 2000

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Abstract

We present progress towards building a test-bed allowing the use of multimedia applications (e.g. web access, voice telephony) running on commercial handheld and palmtop PCs. The handheld units communicate with each other and with the fixed IP network using an ad-hoc networking protocol derived from the Dynamic Source Routing (DSR) algorithm running on simple short-range radio modules developed by the project team. We review the main features of existing ad-hoc protocols, and go on to describe both the existing protocol implementation based on DSR and also the future direction of our protocol development effort.

2. Introduction

This report outlines progress on Air Force funded activities within our research group aimed at developing a prototype ad-hoc network using commercial off-the-shelf technology that will allow users of handheld computers equipped with wireless interfaces to use common networked multimedia applications.

A major goal of the project is to develop a test-bed that we can use to realise our new designs for ad-hoc networking protocols and to make comparisons between new and existing protocols. We have made considerable progress on this and we present an outline of the test-bed in the following sections, before detailing progress on the design and development of an ad-hoc protocol derived from the Dynamic Source Routing protocol. Finally we review the direction of the project and discuss the work that will be carried out in the time remaining.

2. Test-bed Architecture

Our research group has interests spanning the entire range of topics within wireless communications, from the use of novel mobile aware applications to routing protocol design through to the development of adaptable software radios. In developing a test-bed, we needed to develop a highly modular layered framework that would allow entire building-blocks (e.g. the radio subsystem, the ad-hoc networking protocol or the application layer) to be assembled to fit the problem at hand.

We achieved this by building a 'generic layer' interface that allows the dynamic assembly of a stack consisting of hardware and software elements. This allows us to develop, for instance, a range of ad-hoc networking modules that can be debugged using an emulated broadcast network implemented on a segment of Ethernet, later field tested on a real radio link and finally operated across a radio link implemented using software radio techniques.

2.1 Software

We are targeting our software to run on commodity desktop workstations and handheld computers running either Microsoft Windows NT or Windows CE and thus our programming support environment is based on Win32. Using the multi-threading and synchronisation facilities available in this environment, we have designed a generic layer architecture where each layer runs as an independent thread and interacts with its neighbouring layers in very simple, clearly defined ways. A typical layers might implement an ad-hoc routing protocol, a WWW-proxy application or an emulated radio network layer. Our software radio will be realised by combining a sequence of 'transformer' layers that will each carry out a single well-defined signal processing operation on the data passing through.

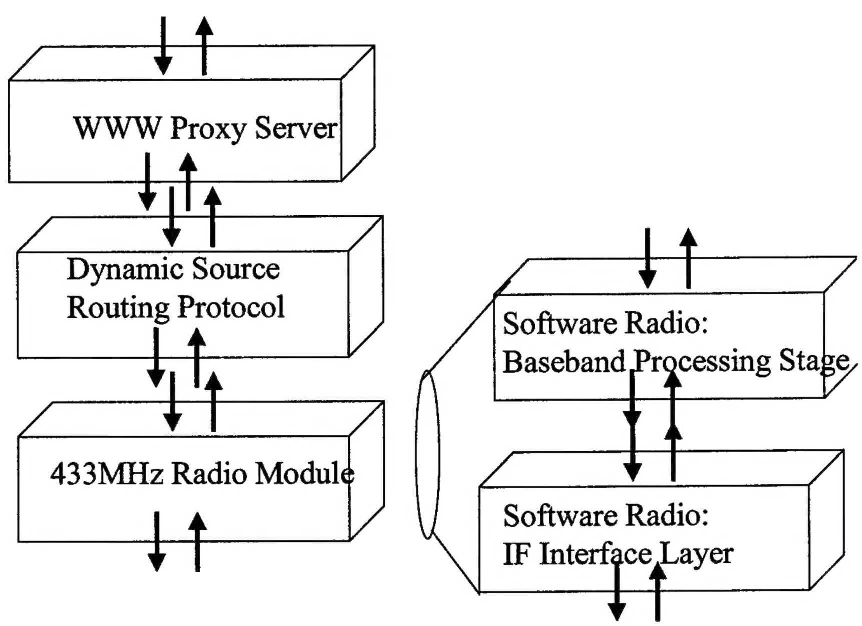

Figure 1: Some typical layers and the interchange of a real and software radio modules

Figure 1 shows a typical set of layers, each implemented independently and then assembled at runtime to form a complete protocol stack. The diagram also shows how a

layer representing a real 433MHz radio can be swapped out and replaced with a stack implementing part of the radio in software.

2. 2 Hardware

The nodes in an Ad-hoc network must be lightweight and portable but at the same time be capable of performing significant processing. For these reasons, we are using Hewlett Packard Windows CE based machines (in both handheld and palmtop formats) as the main nodes in our network. Figure 2 shows two samples of these. The machines are based on Hitachi SH3 RISC processors and are equipped with RS-232 interfaces and audio hardware – which makes them ideal for our purposes.
They are programmed using the Win 32 API with which we have considerable expertise. We expect that all of our software and hardware will migrate easily to the next generation of Pocket PCs when these become available. The use of Win 32 also allows us to use the richer development environment of Windows NT and Windows 2000 for the bulk of the initial testing.

Figure 2: Target Hardware – Commodity Windows CE machines in Handheld and Palmtop formats

The PDAs are equipped with low powered 40 kbit/s, 433 MHz radios developed by the project team. The radio circuit together with the power supply has approximate dimensions 2cmX8cmX6cm and can be fixed easily to the back of the handheld device. The HP PDA communicates with the radio via the serial port. Figure 3. shows the radio subsystem in prototype form.

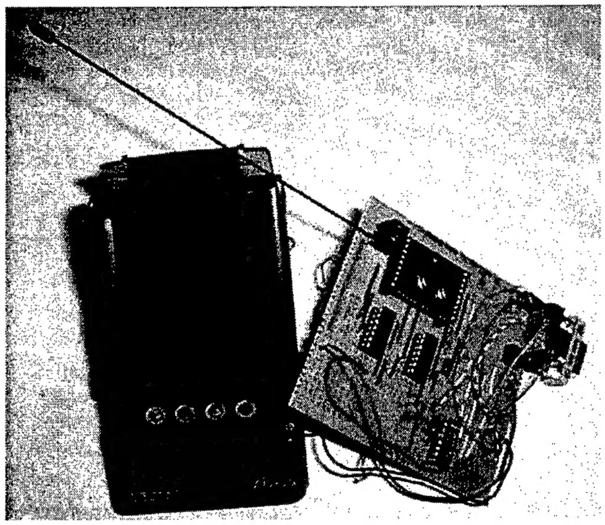

Figure 3: An Early Prototype of the Radio Subsystem

While it is not an integral part of this project, work on the design of low profile antennas for use with this system is also taking place.

3. Review of existing Ad-Hoc Protocols

Ad-hoc routing protocols can be divided up into two distinct categories, proactive (or table based) routing and reactive (or on-demand) routing strategies. Proactive strategies try to maintain an up to date routing table in each node at all times whereas reactive strategies only create routes on demand. Some protocols, such as the Zone Routing Protocol, are explicit hybrid proactive/reactive systems that route to near by nodes with a proactive strategy and to distant nodes with a reactive strategy.

Ideally, an ad-hoc network will have maximum connectivity and throughput between nodes with a minimum of signalling overhead. There are many more factors which are important in describing an ad-hoc network. These factors include link capacity (bits per second between nodes), network size (number of nodes), network connectivity (average degree of a node), topological rate of change (modes moving around a lot or staying in one place for a long time), fraction of unidirectional links, traffic patterns and type (bursty web traffic, periodic sensor data, voice or multimedia streams, multicast traffic) and sleeping patterns (battery conservation issues). Depending on the values of these factors, some routing algorithms will under certain network conditions be more efficient than others.

Listed here are short summaries of some of the more popular ad-hoc routing protocols.

ABR - Associativity Based Routing

- On demand source routing
- ABR tries to derive longer-lived routes
- Each node periodically beacons. Receiving nodes increment associativity tick counters with respect to transmitting node. A high number of ticks mean stable/long lived connection.

SSA - Signal Stability-based Adaptive Routing

- On demand source routing
- Similar to ABR; it tries to find most stable network routes
- The selection of route is based on signal's strength and a nodes 'stability' (ie. it isn't moving about quickly breaking links).

DSDV - Dynamic Destination-sequenced Distance-vector Routing protocol

- Table based routing
- Each node maintains a full table of all available destinations, number of hops to destination and a sequence number assigned by the destination
- Routes with the highest/most recent sequence numbers are used
- Tables are periodically shared with neighbours and sometimes a 'full dump' may take place.

WRP - Wireless Routing Protocol

- Table based routing
- Every node maintains a distance table, routing table, link-cost table and message retransmission list
- Routing tables are exchanged with neighbours periodically and upon link changes.

RDMAR – Relative Distance Micro-Discovery Ad Hoc Routing Protocol

- On demand source routing
- RDMAR localizes query flooding by knowing the relative distance (RD) between two terminals
- RD = last RD value + average nodal mobility + time_last_communicated

CBRP - Cluster Based Routing Protocol

- Based on source routing
- CBRP uses a hierarchical topology that may scale better that flat network
- Groups of nodes elect cluster heads. The groups maintain neighbour tables internally and the cluster heads perform source routing to other cluster heads.

AODV - Ad hoc On-demand Distance Vector Routing

- On demand source routing
- Not unlike an on demand version of DSDV
- Destination Sequence Numbers are maintained for each route entry. DSNs are exchanged using periodic HELLO messages.

- DSNs ensure loop-free routing

DSR - Dynamic Source Routing
- On demand source routing
- Routes formed purely on demand – no periodic broadcasts
- In lower traffic situations DSR is efficient do to less signaling overhead.

ZRP - Zone Routing Protocol
- Hybrid on-demand reactive and table driven proactive routing
- Proactive routing in 'local' area or 'zone radius' (max number of hops from a node).
- Beyond local radius it becomes inefficient to maintain full routing tables (too much data, to many updates mean high signaling overhead) so 'bordercasting' mechanism propagates route queries though the rest of the network.
- Zone radius can be adjusted to give optimal performance.

Another important metric when deciding which ad-hoc routing protocol to choose is ease of implementation. Many of the more complex protocols are optimized for a particular mobility or node distribution scenario. We are primarily interested in having a robust core protocol that works realonably well in many different situations and can be extended in the future. The Dynamic Source Routing protocol was chosen as our initial base as it was one of the more simple and straightforward routing protocols.

4. Implementation

4.1 DSR Implementation

The routing algorithm that we implemented as a component of the software stack is an improved version of standard Dynamic Source Routing (DSR) protocol. As with all ad-hoc protocols it allows nodes to discover a route across multiple network hops to any destination in a mobile network. DSR is just one of many ad-hoc routing algorithms mentioned in the review of existing ad-hoc protocols above.

DSR is an on-demand protocol that reacts to a specific demand to dynamically establish a route from one node to another, unlike table-driven protocols that try to ensure that all nodes maintain up to date information on the changing topology of the network. When the source node receives a demand to route data to a target node a route request floods the network seeking the target node. As the route request propagates through the network it appends the address of every node through which it passes. When the route request reaches the target node a route reply is then sent back to the source node along the route through which the successful route request had been propagated. When the source has received the route reply it may then attempt to route all the data using the route contained in the route reply.

In the standard implementation of DSR, intermediate hops are not required to maintain routing information in order to route data packets as all the routing information is

contained in the header of the packets being routed. As the intermediate hops are not relied upon to provide this routing information during the data routing phase, the need for periodic router advertisements that update nodes on the status of the network topology, is eliminated, reducing the overhead of this algorithm. If it happens that a route becomes invalid owing to the inherent changing topology of the mobile network then a new route request can be originated to establish a fresh route to the target. The DSR algorithm makes use of lightweight route maintenance procedures that are not as extensive or as costly as those employed by the table-driven protocols. The localised use of route error reporting mechanisms and routing acknowledgements allows for essential route maintenance only. The failure of a node is only reported to those nodes directly concerned with the routing of the data in question.

While the standard DSR algorithm does not actively engage in an effort to maintain accurate topology knowledge for each node at all times, there are certain procedures that can be implemented to utilise existing information being circulated through the network in an attempt to increase the efficiency of the algorithm. Intermediate nodes, which are otherwise acting as packet repeaters, and idle nodes that are within broadcast range of a transmitting node, can eavesdrop on the routing information contained in the packets that are being propagated through the network. Nodes may choose to eavesdrop if they have the power capacity to do non-essential tasks and if they are not called upon to process packets that are actually destined for them. The advantage of this eavesdropping is that if these nodes are then required to route data themselves, they may have already cached the appropriate routes during this eavesdropping process, eliminating the need to flood the network with further route requests. This process does not increase the overhead of DSR and is not a cause of network congestion. Whereas table-driven algorithms involve the use of separate route maintenance and data routing procedures, the algorithm implemented here makes the most efficient use of the routing information and bandwidth available to it. While this does not ensure that each node has a comprehensive knowledge of all routes leading from it, it means that nodes do have knowledge of those local routes that are actively being used to transmit data.

An experimental evaluation environment was created to test the stability and effectiveness of the routing protocol. This environment consisted of both mobile and static nodes. The DSR protocol was implemented in such a way that it could be used and tested over various physical layers, whether real or simulated. A 'datagram' layer, based on the use of sockets, enables the simulation of physical media such as radio broadcasting and IrDA, by configuring a node sockets appropriately. Such simulations allow for the robust testing of the routing protocol before field trials commence.

4.2 Experimental Setup

The in-house designed test-bed, outlined in section 2, is used to evaluate the performance of the ad-hoc network routing protocols in which we are interested. Figure 4 gives an overview of the current test scenario. The system consists of a wireless ad-hoc network that contains a node with access to a fixed network. This is typical of what would be expected in a fully functioning ad-hoc environment.

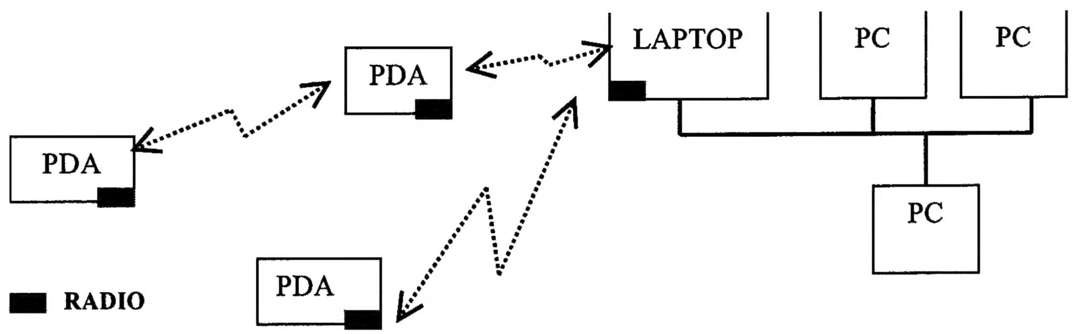

Figure 4: Experimental Set-up – Scenario 1

The appropriate layers are placed in each node of the network and assembled at runtime to form a complete protocol stack. The layers in the main nodes are shown in Figure 5. In the wireless ad-hoc network the layers of the communication stack consist of an application layer, an encryption layer (blowfish), an ad-hoc routing layer (DSR) and a radio API layer. The access point or gateway node between the wireless and wired networks contains two stacks. Data arrives from a wireless node via the radio API layer and passes through a relay layer and is broadcast to the fixed network through the datagram layer. All other nodes in the fixed network have a datagram layer, a DSR layer, a blowfish layer and some have application layers.

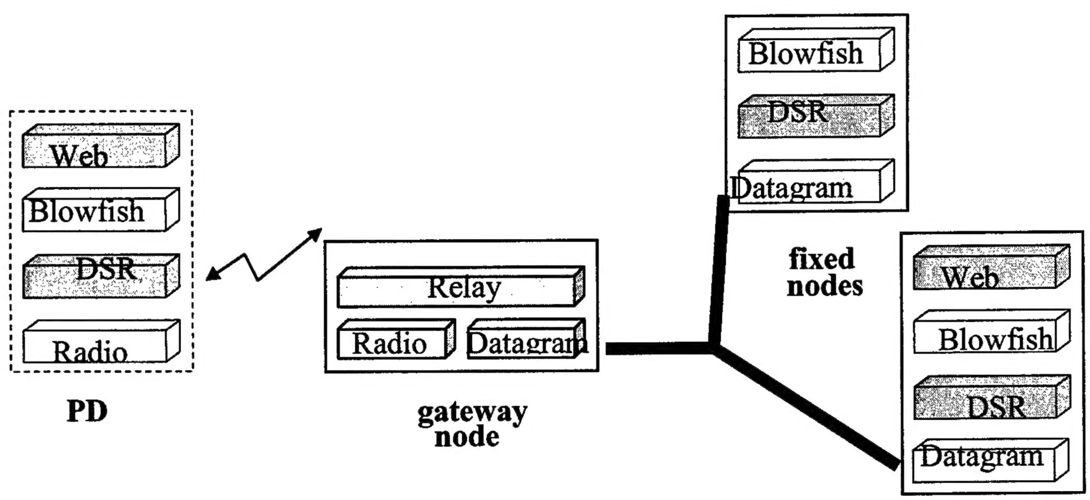

Figure 5: Experimental Set-up – Communication Stacks Details

By using this approach we can assess interaction between wireless and wires nodes, the protocol performance over a real wireless channel as well as having the option of greatly increasing the number of nodes in the network in order to effectively test the scalability of the DSR protocol.

4.3 Future Work

Presently, we have constructed a working wireless ad-hoc network based on the Dynamic Source Routing protocol. In the remaining months of the project, we will consolidate and stabilize this work as we enter a phase where we can experiment with the protocol in a variety of mobility scenarios.

We plan to extent the base protocol to incorporate some of the features found in other routing protocols.

These features may include:

- Zone Routing

  As the network size increases some form of balancing the useful effects of close range table driven/proactive routing with long range demand/reactive routing may lead to less signalling traffic on the network as a whole. The approach taken by ZRP allows a radius around a node beyond which ZRP switches from a proactive to reactive routing protocol.

- Signal stability

  By making use of signal level readings or the past error performance of links, we may be able to determine more accurately which nodes are best suited for transit routing. Also, by using associativity parameters such as ABR's ticks, nodes that are 'passing though' the system may be avoided to route traffic though. By avoiding these transient or unstable nodes the overall signalling traffic of the network is reduced.

- Forward Error Correction

  Small amounts of Forward Error Correction (FEC) in some situations will make great savings on wasted retransmission traffic. We will implement an FEC module for our stack ("Smart Reliability Layer") to help alleviate retransmissions due to simple bit errors in transmitted packets.

In addition to our experimentation with ad-hoc protocols, we are interested in exploring the security aspects of wireless applications that will run on ad-hoc networks. Whenever a population of wireless nodes forms an ad-hoc network, this necessarily implies the formation of an ad-hoc group of identities that must be mutually authenticated and dynamic maintenance of this networked group. We would also like to pursue the use of different applications that can profit from the ad-hoc nature of the network.